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Digital transmission tests of multiplexed video and audio signals at 60Mbit/s via the Orbital Test Satellite (OTS)

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Summary

This report describes a series of experiments carried out during March 1979 in which 60 Mbit/s digital television signals were transmitted via the OTS from Goonhilly Downs Satellite Earth Station. In these experiments, the error rate in the digital television signal was measured over a range of system operating conditions which included simulations of co-channel and adjacent-channel interference from other satellite channels. Particular reference is made to those operating conditions which are specified for large earth stations in the future European Communications Satellite (ECS) system.

Issued under the authority of

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Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION
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1. Introduction

At present, video signals are distributed nationally and internationally using analogue f.m. techniques. In future, the alternative use of digital modulation techniques offers the possibility of improved performance and reduced cost for video transmission, in particular when the transmission link covers large distances. To gain practical experience, a number of field trials involving experimental transmissions of multiplexed video and sound signals using digital techniques have already been made by the BBC in conjunction with the UK Post Office, over cable, satellite and optical fibre links.[1,2,3]

Trials of digital television and sound transmission via a satellite repeater took place in May 1976 and were conducted from the UK Post Office, Goonhilly Downs Satellite Earth Station. The satellite was of the Intelsat IV type with a transponder link capacity of 60 Mbit/s. The BBC test signal comprised a 60 Mbit/s 'package' providing one video channel multiplexed with six high-quality sound channels. These trials emphasised the value of testing a link with real digital video signals as it was found that the highly-structured nature of the information could cause difficulty in demodulation of the received carrier. It was also shown that over certain ranges of operating conditions, digital transmission gave a slightly better subjective picture quality than f.m. transmission.

From 1983 a European Communications Satellite (ECS) system will provide satellite links for digital telecommunication traffic and for television transmission within Europe. The ECS system will differ in many ways from the Intelsat IV system and an Orbital Test Satellite (OTS) was launched in May 1978 in order to test the new operating systems to be incorporated in the ECS. Although it is planned that television transmission will use analogue f.m. it is nevertheless of considerable interest to determine the performance of the satellite link for digital television signals over a range of possible operating conditions.

This report describes some further 60 Mbit/s digital video and sound transmission tests, that were conducted by the BBC together with the UK Post Office at Goonhilly using the OTS in March 1979. The aim of these tests was to investigate as fully as possible in the time available the properties of the future European satellite system in relation to digital television transmission.

2. ECS system parameters

2.1. General

In the ECS system, the satellite will have 6, nominally 80 MHz frequency bands with a minimum spacing of 83.33 MHz between bands. Each frequency band will be used by two channels on separate orthogonal linear polarisations of the radio-frequency carrier (this is termed 'frequency re-use') and each of these channels will have a digital transmission capacity of 120 Mbit/s using 4-phase phase-shift keying (p.s.k.) modulation. The up-link and down-link carrier frequencies will be in the 14 GHz and 11 GHz frequency bands respectively.

For the up-link, an ECS-system earth station will use typically a 2 kW transmitter amplifier (klystron or travelling-wave tube) in each channel, run with an output back-off from saturation of at least 3 dB. The satellite repeater will use 20 W travelling-wave-tube amplifiers run at saturation in each channel.

2.2. Television transmission

At present, it is planned that television transmission in the ECS system will be via the wide coverage 'Eurobeam' satellite aerial which is approximately similar in coverage area to the 'Eurobeam A' aerial of the OTS described in Section 3.

From signal-to-noise considerations for f.m. television transmission, system planners estimated that the clear weather, carrier-to-noise ratio requirement for the ECS system was 19 dB* (in a bandwidth of 36 MHz).[4] This carrier-to-noise figure should ensure a weighted video signal-to-noise ratio of 53 dB for 99% of the time, assuming

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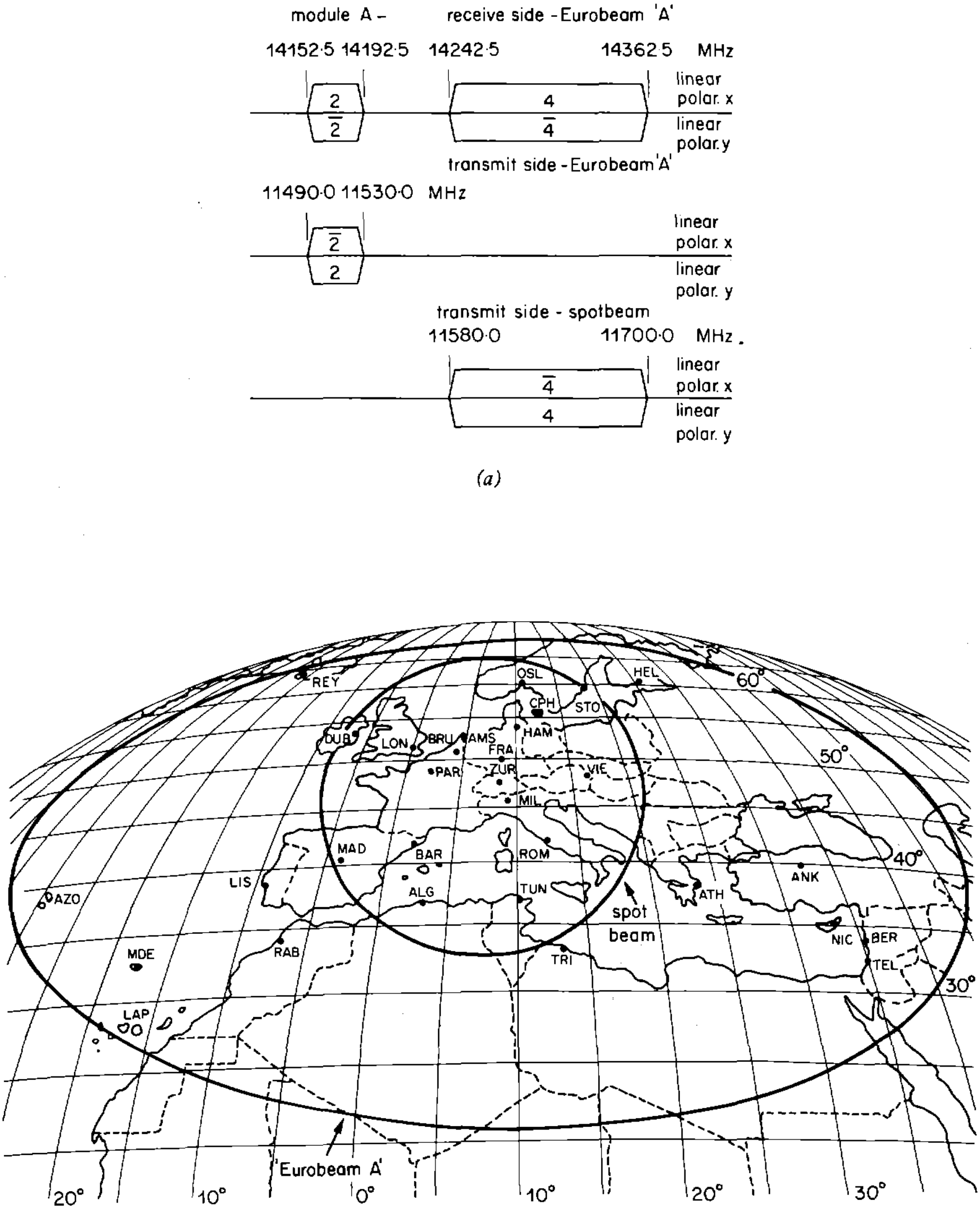
* A 19 dB carrier-to-noise power ratio might be expected, for example, at an ECS system station which is situated at the edge of the coverage area of the ECS 'Eurobeam' antenna and which has a 15m diameter aerial together with a parametric amplifier with a noise temperature of 200 K°. A similar station in Europe or south-east England would give a 2 or 3 dB greater carrier-to-noise figure.



(b)

Fig. 1

(a) Frequency plan for OTS channels 2/$\overline{2}$ and 4/$\overline{4}$

(b) Approximate coverage areas (to –4 dB beam edge) of OTS 'Eurobeam A' and 'Spotbeam' aerials

the transmission of a single television carrier per satellite transponder channel.

During joint EBU and Interim Eutelsat tests of analogue f.m. television transmission via the OTS,[4] this figure of 19 dB (in 36 MHz) was taken as representative of the clear weather, carrier-to-noise ratios at large earth stations in the ECS system when receiving television transmissions via the wide coverage 'Eurobeam' satellite antenna.

2.3. Digital television transmission via the ECS

The 120 Mbit/s capacity of an ECS channel may be used to carry two separate digital television and sound signals, in the form of two interleaved 60 Mbit/s digital video 'packages'. Alternatively, a channel may be used to carry a single 60 Mbit/s video signal occupying half the available channel bandwidth. This latter option may be advantageous because it provides increased noise margins. This is discussed further in Section 6.

2.4. Interference between channels

As a result of the dense packing of channels in the ECS, there will be a degree of interference between channels consisting mainly of two types; (a) co-channel interference and (b) adjacent-channel interference. Co-channel interference can occur between the two channels using the same carrier frequency when the discrimination between the orthogonal carrier polarisations is reduced, for example as a result of atmospheric depolarisation. Adjacent-channel interference occurs between signals which have parallel polarisations and adjacent-channel frequencies, and is aggravated by non-linearity in the response of the ground station high-power amplifier, which causes spreading of the signal spectrum into adjacent channels.

3. OTS system parameters

3.1. General

The OTS systems are similar to those planned for the ECS network except that the OTS has four wideband channels; two with a 40 MHz bandwidth and two with a 120 MHz bandwidth. A frequency plan for these channels is shown in Fig. 1 together with the service coverage areas of the OTS antennae.

Also, the aerial used for the OTS system tests at Goonhilly has a diameter of 19m giving a larger gain than a typical ECS station aerial (which, for a large earth station, will have a diameter of around 15m). However, using the OTS and the Goonhilly Downs Earth Station, operating conditions approximating to an ECS system could be simulated.

3.2. Goonhilly Downs OTS station

A block diagram of the OTS system equipment for transmitting and receiving digitally modulated signals is given in Fig. 2.

There are two complete transmit chains; one is designed to cover the 40 MHz channels 2 or $\overline{2}$ whilst one is to cover the 120 MHz channels 4 or $\overline{4}$. However, the channel frequency of either chain can be varied to other up-link frequencies; for example, the two chains were used to transmit signals on both Channels 2 and $\overline{2}$ during cross-polar interference tests. For 60 Mbit/s data transmission, the data, accepted in the form of two 30 Mbit/s streams, is differentially encoded and then modulated onto a 70 MHz intermediate frequency (i.f.) carrier, using 4-phase phase-shift keying. This carrier is sent across site to the aerial building where it is up-converted to the 14 GHz band, amplified through 2 kW klystron amplifiers and fed to the OTS aerial. The radiated power could be varied either by changing the input drive to the klystrons or by absorbing a fraction of the output powers in a variable high-power attenuator. The outputs of the two chains normally feed orthogonal polarisations of the aerial, although they may be combined into a single feed in order to simulate various interference conditions.

On the receive side, the 11 GHz signal from the satellite is amplified (using a Peltier-cooled low-noise amplifier) and down-converted to 70 MHz before demodulation. Noise can be added to this 70 MHz signal to simulate degraded carrier-to-noise conditions. The demodulator recovers a 70 MHz carrier signal which is used to coherently detect the received data and then recovers a 30 MHz clock signal. The latter is used to re-sample the demodulated data and regenerate two clean 30 Mbit/s data streams. These data streams are differentially decoded in order to resolve the four-fold phase ambiguity of the detection scheme.

3.3. OTS description

On board the satellite, one module, module A, services the two 40 MHz and the two 120 MHz bandwidth channels. A second module, module B, contains transmit and receive equipment for 5 MHz bandwidth channels. These 5 MHz channels were not used in the present series of tests.

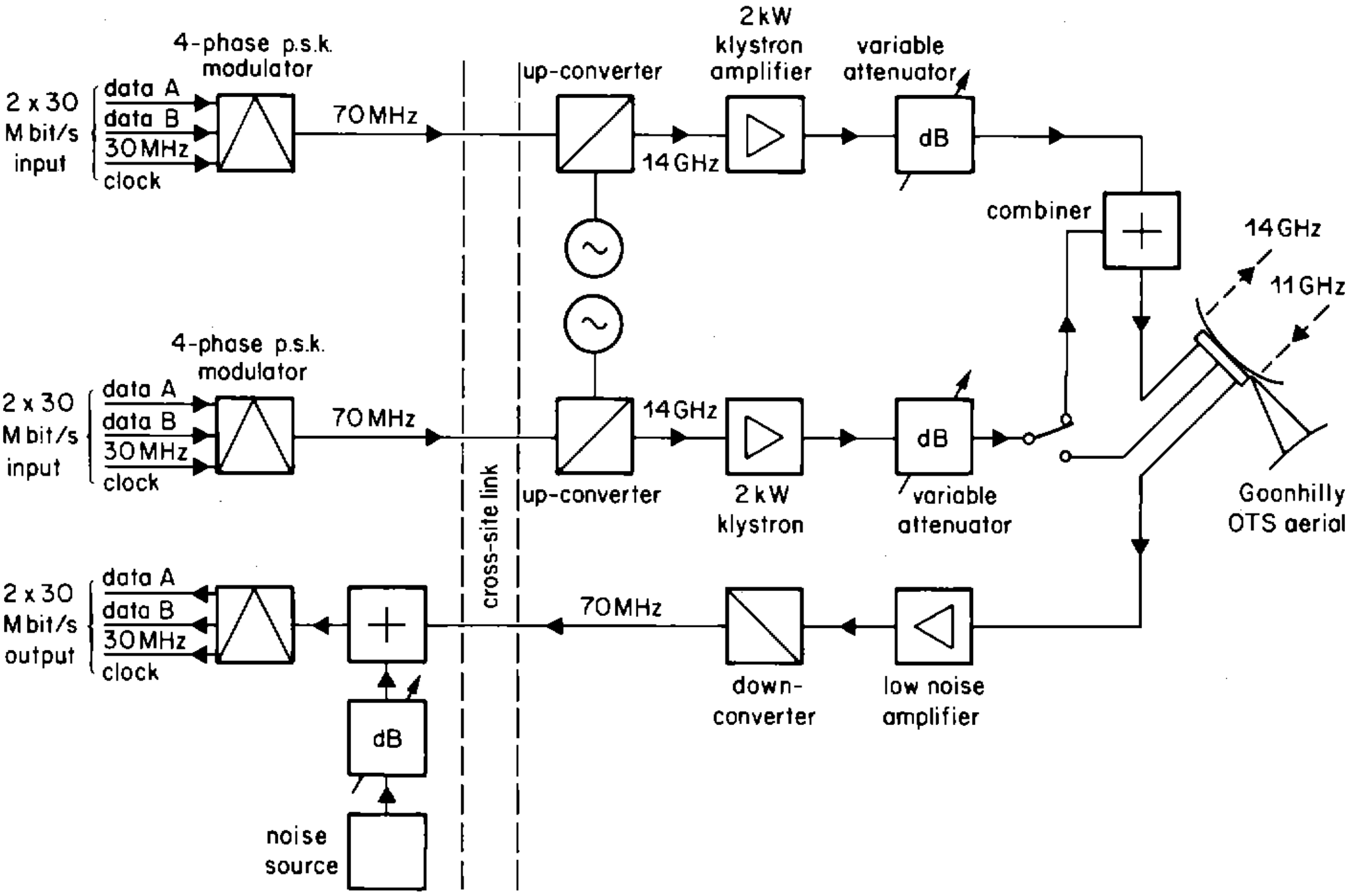


Fig. 2 - Post Office equipment for transmission and reception of digitally-modulated signals via the OTS

Fig. 3 shows in outline a single 40 MHz channel in module A. The first stage is a low-noise receiver which amplifies and down-converts the up-link signal in the 14 GHz band to an intermediate frequency of around 1 GHz. A demultiplexing filter then selects the individual channel signal prior to pre-amplification and up-conversion to the 11 GHz band. The overall gain of the channel transponder may be varied in several steps over a range of about 15 dB. The relative transponder gains for different gain-step settings are given in Appendix A. The channel has a travelling-wave-tube amplifier (with 20 watt output power at saturation) after which the signal is combined with the output from the second 40 MHz channel and fed to the Eurobeam A satellite antenna. At the output of each channel there is a multiplexing filter to limit interference between adjacent channels. This basic arrangement is the same for the two 120 MHz channels except that the channel outputs are transmitted via the 'spotbeam' satellite antenna.

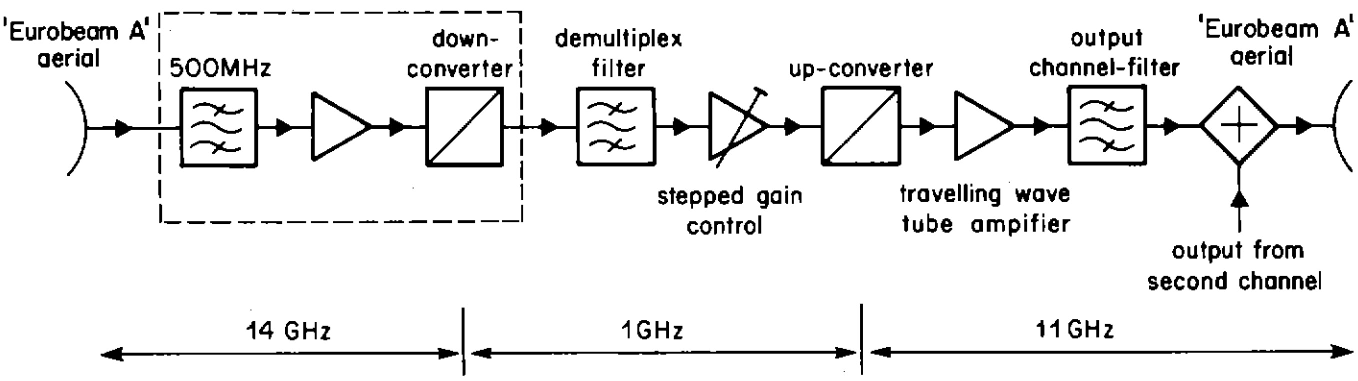


Fig. 3 - Outline of satellite repeater channel

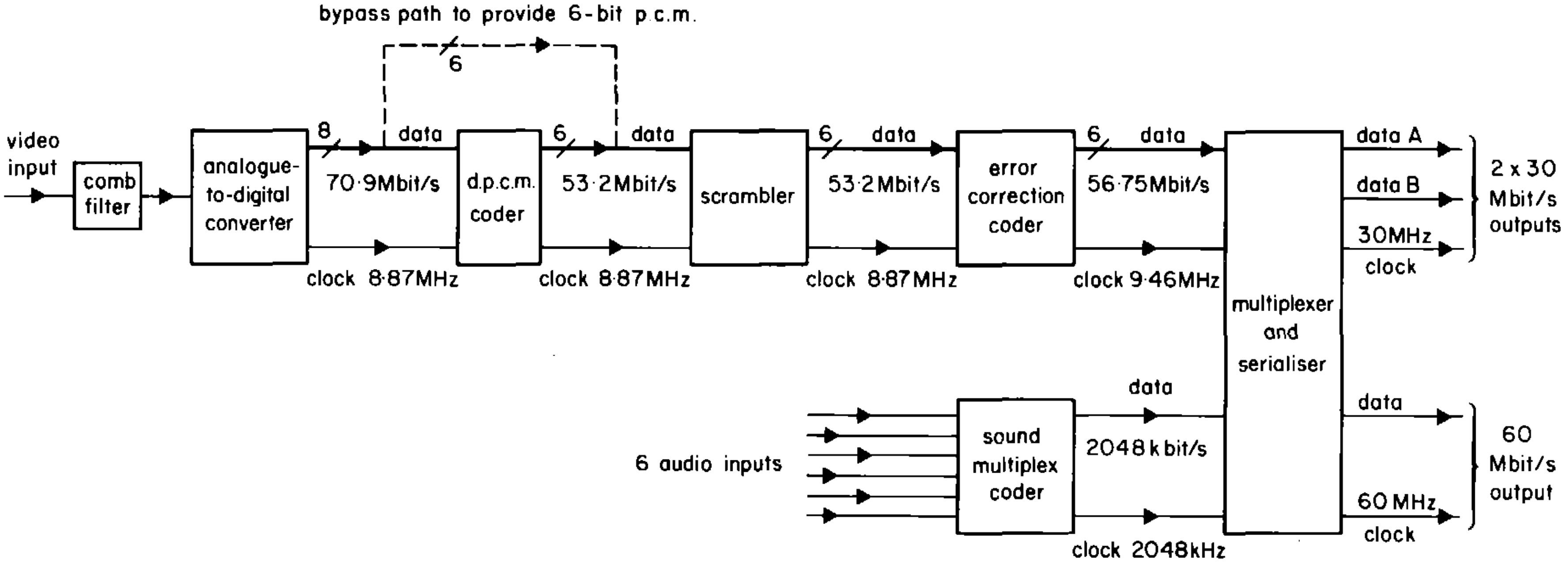


Fig. 4 - BBC 60 Mbit/s multiplex block diagram

Unfortunately, the travelling-wave tube amplifier in Channel $\overline{2}$ was faulty so that this channel could not be used for down-link interference studies.

4. BBC experimental 60 Mbit/s system

The BBC multiplex equipment assembled a 60 Mbit/s package which carried one video signal and up to six high-quality sound signals. The equipment was largely the same as that which was used for the field trials of digital television transmission via an Intelsat IV satellite in 1976.[2]

A system I PAL video signal was coded using a combination of sub-Nyquist sampling and differential pulse-code modulation (d.p.c.m.) techniques.[5] A block diagram of the equipment used is given in Fig. 4. The video signal was sampled at twice colour-subcarrier frequency and differentially coded to 6-bits per sample for transmission. The signal was passed through a self-synchronising feedback scrambler and then given a degree of error protection by the addition of a (16,15) Wyner Ash error-correcting code.[6] This code was designed to correct random bit errors and also short burst errors of up to six successive bit errors in the demodulated 60 Mbit/s signal.

The sound signals were sampled at 32 kHz and coded using a near-instantaneous companding technique[7] giving 10 bits per sampled word. Six such sound signals were multiplexed together to produce a 2048 kbit/s signal.

The final 60 Mbit/s signal was assembled by multiplexing the video and sound data together with framing and justification control. Justification was required since the input and output bit rates were unrelated and could vary independently within certain tolerances.[8] The 60 Mbit/s output was formed into two 30 Mbit/s streams as required by the Post Office 4-phase p.s.k. modulator. The multiplex equipment also had a second 60 Mbit/s channel which was used to provide a separate source of digital television data for a second satellite channel during up-link interference measurements.

The receiving equipment was complementary to the sending equipment.

Facilities were provided in the receiving equipment for continually monitoring the transmission path bit-error rate whilst video signals were being transmitted. The Post Office also provided equipment to measure the bit-error rate and to provide information about the probability distribution of errors. This equipment however, generated its own television-like test sequence and compared, bit by bit, the received and transmitted data.

Standard television test pictures for transmission over the satellite were obtained from the BBC Designs Department in London via a Post Office video link. An off-air receiver and an electronic test pattern generator provided alternative local sources of video and a portable high-quality video tape recorder* was used to record test results.

5. Scrambling

Some preliminary tests were carried out to determine the degree of scrambling[2] of the video data that was required for optimum performance of the Post Office 4-phase p.s.k. modulation and demodulation equipment. Previous trials of digital television transmission had shown that the highly-structured nature of video data could cause clock-recovery problems at the demodulator giving rise to increased bit-error rates.

Initially therefore, the BBC 60 Mbit/s signal was passed through the modulator and demodulator, which were connected back-to-back at the 70 MHz i.f. stage. Various pictures were selected as source material and the data was coded using 6-bit d.p.c.m. or 6-bit p.c.m. The degree of scrambling of the video data was varied by adjusting the number of stages in the scrambler circuits.

The scrambler was effectively six self-synchronising feedback scramblers in parallel, one inserted in each of the six parallel bit streams at the input to the Wyner-Ash error-corrector coder. A complementary de-scrambler arrangement was used in the 60 Mbit/s decoding equipment at the output of the error corrector.

With no scrambling of the data, the four-phase p.s.k. modem alone introduced an error rate of about 1 in 10^4 for video coded using d.p.c.m. For video coded using p.c.m. the modem failed completely to pass some test pictures. With scrambling, the performance improved steadily as the number of elements in the scrambler was increased. It was found that six-stage scrambling was required for the modem not to introduce errors into any 60 Mbit/s data.

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* Provided by Ampex of Great Britain Ltd.

6. Satellite transmission

The main transmission tests took place at Goonhilly between the 20th February and the 1st March 1979. During this time, digital television signals were transmitted via the OTS and the link bit-error rate was monitored over a range of possible operating conditions.

This Section outlines the variable parameters which determine the performance of a satellite link and describes the results of the tests which simulated changes in these parameters. The first section discusses single-channel performance and the next two sections describe the effects of possible co-channel and adjacent-channel interference.

6.1. Single-channel performance

6.1.1. General

The main factors which determine the link performance and which are likely to vary from station to station and with local weather conditions are the received carrier power-to-noise power ratio and the level of non-linearity in the high-power amplifiers in the channel.

How these factors vary is discussed more fully below.

6.1.2. Carrier-to-noise power ratio

The received carrier power and total noise power are themselves functions of several factors. These typically are:

(i) Earth station aerial diameter
(ii) Atmospheric thermal noise level
(iii) Receiver noise factor
(iv) Signal bandwidth – The noise power is proportional to the bandwidth of the filters defining the signal bandwidth at the input to the demodulator
(v) Down-link carrier power flux – For a given receiving station and given satellite antenna the received carrier power will vary with local weather conditions which can cause fading or depolarisation of the 11 GHz down-link carrier.
(vi) Up-link carrier power and up-link noise contribution – The carrier power received by the satellite can fade as a result of weather conditions local to the transmitter. An up-link fade causes an increase in the contribution of up-link noise to the overall carrier-to-noise ratio, and also some reduction in down-link power.

For digital transmissions, the ratio of carrier power to noise power is commonly expressed as a ratio of 'energy per bit to noise power per unit bandwidth' (E/N_0). This definition makes it easier to compare the performances of different digital transmission systems. Appendix B describes how E/N_0 values are related to carrier-to-noise ratios. In this report, the E/N_0 values were calculated from measured carrier and noise powers assuming a bit rate of 60 Mbit/s. For comparison with analogue television transmission figures, these E/N_0 values may then be converted to equivalent carrier-to-noise ratios (for a signal bandwidth of 36 MHz) by adding 2.2 dB.

For example, the carrier-to-noise ratio of 19 dB, taken as a representative figure for f.m. television reception at large ECS system earth stations, corresponds to an E/N_0 value of 16.8 dB for 60 Mbit/s television transmissions. Under the same transmission and reception conditions the E/N_0 value for 120 Mbit/s transmissions would be 13.8 dB.

6.1.3. Non-linearity of high power amplifiers

The channel performance is degraded as the level of non-linearity in the ground-station amplifier or the satellite travelling-wave-tube amplifier is increased. This degradation is a product of spectrum spreading caused by the non-linearities, in conjunction with the band-limiting of the spectrum by channel-shaping filters.[9]

The output power level required from a ground-station high-power amplifier will depend on the gain of the transmitting aerial and also on any losses incurred in combining the outputs from separate channels. In an ECS system station the output power from the transmitter amplifier will be typically half the saturated power output. As a result of the large overall gain of the Goonhilly aerial, sufficient power to saturate the satellite could be radiated with the ground-station klystron amplifier operating well away from saturation. However, with the OTS system, the klystron output could be varied up to saturation while the EIRP* was maintained at a lower level by absorbing a fraction of the output power. The operating point of the klystron was defined in terms of the *output* power back-off (in dB) from the saturated power output.

On board the satellite, the travelling-wave tube amplifier was run at, or nearly at, saturation. Up-link power fading reduced the input drive to the travelling-wave tube causing a reduction in its level of saturation. The operating point of this amplifier was specified as an '*input* back-off' which refers to the ratio (in dB) measured at the amplifier input, between the received carrier power and that carrier power which was just sufficient to saturate the amplifier output.

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* EIRP – Equivalent Isotropically Radiated Power.

6.1.4. Single channel measurements via the OTS

60 Mbit/s digital television signals were transmitted and received via Channel 2 and the bit-error rate was monitored at the BBC video demultiplexer. Measurements were taken for a range of possible operating conditions of the ground station klystron amplifier and of the satellite travelling-wave-tube amplifier over a range of link E/N_0 values. These measurements are described in the following two sections.

The E/N_0 value for the link was varied by adding noise at the receiver i.f. stage. In order to measure the E/N_0 value, a narrow-band carrier (swept over 2 MHz) was radiated to the satellite at an appropriate level and the received i.f. carrier level at the input to the demodulator was recorded. The noise level was then measured in a 14 MHz-wide frequency band within the channel but to one side of the carrier signal. The presence of the carrier signal was necessary during this noise measurement because the noise level output from the satellite is a function of the operating point of the travelling-wave tube. The overall E/N_0 figure for the channel could then be calculated.

6.1.5. Link performance and klystron operating point

The bit-error rate was measured under three conditions of non-linearity of the ground-station klystron. These were:

(a) with the klystron run with an almost linear response well away from saturation. This corresponded to the normal operating point of the OTS system and is defined as the 'nominal OTS' condition.

(b) with the klystron run with a 3 dB output back-off from saturation and with attenuation of the output power to maintain the same radiated power as in case (a). This corresponded to the design operating point for typical ground stations in the ECS system and is defined as the 'typical ECS' condition.

(c) with the klystron run at saturation (0 dB output back-off) and the same radiated power as in case (a). Defined as the 'worst-case ECS' condition, this corresponded to an ECS system operating point with the greatest non-linearity which might arise if the ground station output power were to be increased to compensate for a severe up-link power fade.

Typical results for these three conditions are given in Fig. 5. The up-link EIRP was set so that the satellite travelling-wave tube amplifier was just at saturation. Fig. 5 shows how, for a given E/N_0 value, the bit-error rate increased with saturation level of the klystron. For a typical E/N_0 value the bit-error rate increased by roughly an order of magnitude in going from a linear to a saturated klystron operating point.

The dashed curve in Fig. 5 shows, for comparison the theoretical bit-error-rate curve for an ideal, linear system in the presence of Gaussian noise. The performance of the OTS system is approximately 2.5 dB worse than theoretical error rates around 1 in 10^6.

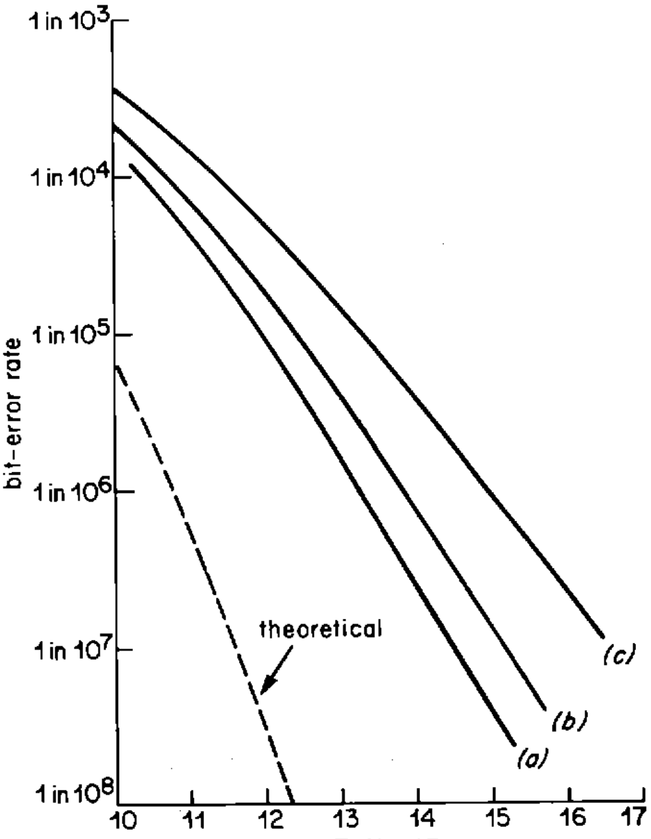

Fig. 5 - Channel 2 performance for different operating points of ground-station klystron

(a) linear (b) 3 dB output back-off (c) 0 dB output back-off
(satellite operation conditions: gain step = 2, input back-off = 2 dB)

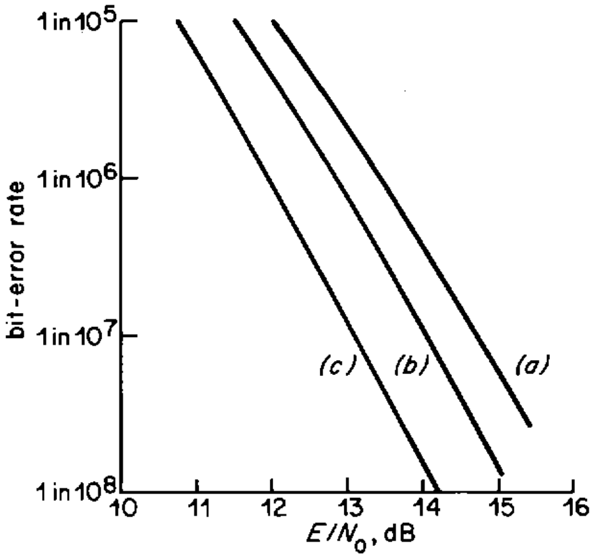

Fig. 6 - Channel 2 performance for different operating points of satellite high-power amplifier

Up-link fade value (input back-off) (a) 0 dB

(b) 5 dB

(c) 11 dB

(Satellite gain step = 2, klystron operating point: linear)

6.1.6. Satellite operating point

Under normal weather conditions the ECS satellite will be run at, or nearly at, saturation. However, poor weather over the up-link path will cause fading of the up-link power which will change the operating point of the satellite.

In order to investigate how the link performance varies when the up-link power fades, the bit-error rate was measured while the operating point of the satellite (measured in terms of the input back-off from saturation) was changed by reducing the up-link power. Fig. 6 shows how the Channel 2 bit-error rate varies over a range of E/N_0 values for three different values of the satellite input back-off. Fig. 6 shows that for a constant E/N_0 value the link performance improved as the satellite input back-off was increased. This is because the operation of the travelling-wave tube became less non-linear as the up-link power was reduced.

However, in the presence of an up-link power fade the E/N_0 value measured at a given receiver will not stay constant but will decrease (a) because as the up-link power fades, the down-link power also decreases (but by less than the up-link power because of the non-linear saturation response of the travelling-wave tube amplifier) and (b) because, as the satellite output decreases, the small-signal (i.e. noise) gain of the travelling-wave tube increases causing the overall noise level to rise.

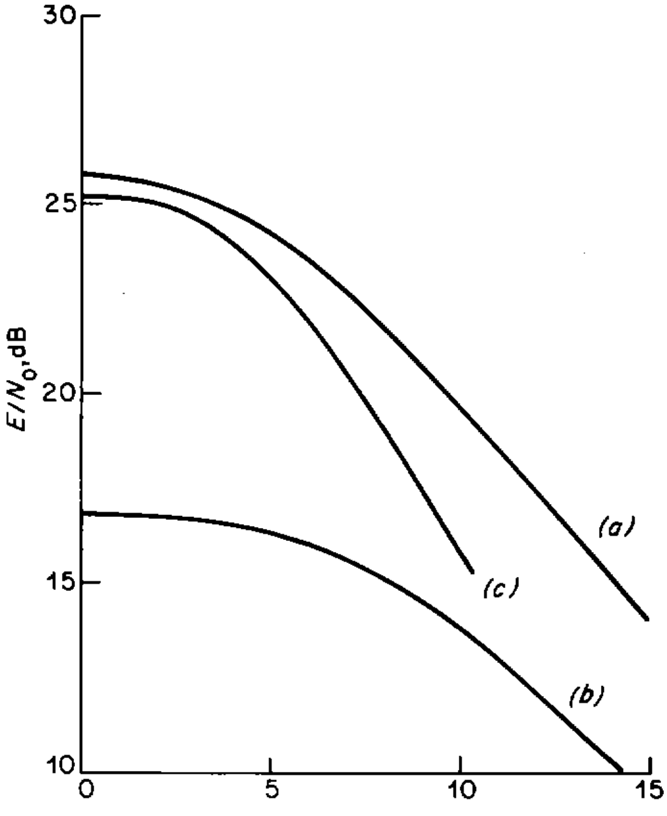

Fig. 7 - E/N_0 variation as a function of up-link satellite input back-off

(a) Nominal OTS system (satellite gain step = 2)

(b) Typical ECS system (satellite gain step = 2)

(c) Nominal OTS system (satellite gain step = 7)

The variation of E/N_0 with up-link fade value was measured for the Goonhilly OTS receiver (i.e. with no added noise) and for a simulated ECS receiver (with noise added to give a clear weather E/N_0 of 16.8 dB). The results are given in curves (*a*) and (*b*) of Fig. 7. The satellite transponder gain setting was at gain step 2 and the up-link fade value was measured in terms of the satellite input back-off value.

Fig. 7(*c*) shows the corresponding E/N_0 variation for the Goonhilly receiver when the satellite transponder gain was increased by changing to gain step 7. The curves 7(*a*) and 7(*c*) differ because the contribution to the total receiver noise level made by the up-link noise was increased by increasing the overall gain of the satellite repeater.

6.1.7. Transmission via 120 MHz OTS channel

For a short while during the period of the present tests, the two 120 MHz-wide channels (4 and $\overline{4}$) were available for use by Goonhilly and some transmission measurements were made sending the 60 Mbit/s television signal via this wider-

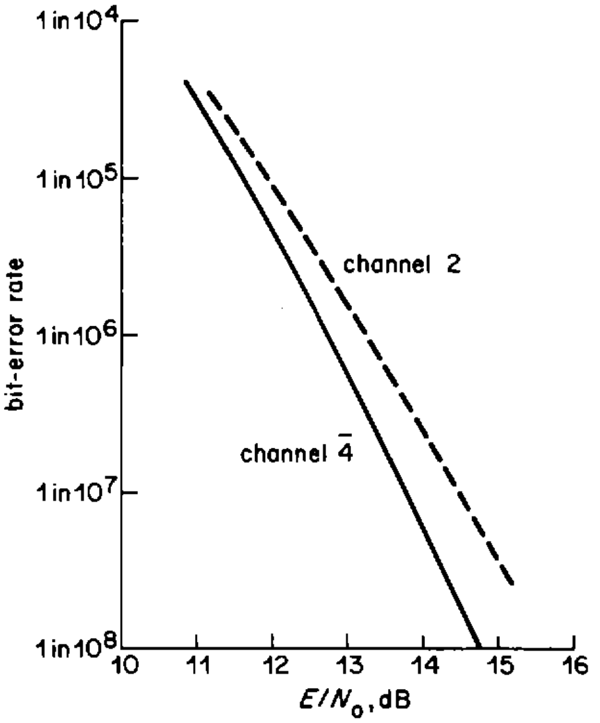

Fig. 8 - Bit-error rate measurements for a 60 Mbit/s signal over OTS Channel $\overline{4}$ *compared with Channel 2 (system operating points: ground-station klystron-approximately linear, satellite — 0 dB input back-off)*

band link. Fig. 8 shows the measured bit-error rate versus the channel E/N_0 value for Channel $\overline{4}$. The dotted curve shows for comparison the Channel 2 performance under similar operating conditions.

Fig. 8 shows that, for a given E/N_0 value, the bit-error rate was smaller in the wider-band channel. The worse performance of Channel 2 was probably caused by the band limiting of the signal by the channel multiplexing filters as this was much more significant in the narrower band channel. Therefore, the transmission performance of Channel $\overline{4}$ was probably more indicative of the bit-error rates that might be expected for 60 Mbit/s signals in an 80 MHz-wide ECS channel than the Channel 2 measurements of 60 Mbit/s transmission through a 40 MHz-wide channel. The Channel 2 bit-error rate measurements correspond more closely with 120 Mbit/s digital television transmission via an 80 MHz-wide channel.

6.1.8. Summary of single channel measurements

The nominal OTS system at Goonhilly had a link E/N_0 value of approximately 25 dB which gave a negligible bit-error rate. In the ECS system, a 'large' earth station having an E/N_0 value of 16.8 dB (for 60 Mbit/s) would have an error rate of less than 1 in 10^8. For 120 Mbit/s transmission this error rate would rise to around 1 in 10^6 because a doubling of the signal bandwidth gives a 3 dB increase in noise power.

From the bit-error rate measurements, system margins were determined in terms of the degradation of link E/N_0 value that could be tolerated before the bit-error rate reached 1 in 10^5; a value taken to be the upper limit for digital television transmission. Corresponding margins were then estimated in terms of the depth of signal fade on either the up-link or down-link path that would give rise to a bit-error rate of 1 in 10^5.

Table 1a gives the E/N_0 margins and the corresponding signal fade margins for systems with operating points corresponding to the nominal OTS system, a 'typical' ECS system and a 'worst-case' ECS system. The nominal OTS system is taken to have a clear weather E/N_0 value of 25 dB and to have a ground-station klystron operating point which is linear. In the 'typical' and 'worst-case' ECS conditions, the clear weather link E/N_0 value is taken to be 16.8 dB and the klystron operating points are 3 dB output back-off and saturation respectively. (These E/N_0 margins are probably pessimistic estimates for large ECS system stations which are situated well within the coverage area of the Eurobeam antenna and which will probably have E/N_0 values of better than 16.8 dB for 60 Mbit/s transmissions. However, the figure of 16.8 dB corresponds to the stated clear weather carrier-to-noise ratio requirements for f.m. television transmissions.)

In Table 1a, the down-link fade margin differs from the E/N_0 margin because the atmospheric noise contribution varies with atmospheric (rainfall) attenuation over the down-link path. The formula used for estimating the atmospheric noise level is given in Appendix C. Also in Table 1a, the up-link fade margins take into account the improvement in link performance (for a given E/N_0) with increasing satellite input back-off.

From these values for the up-link and down-link fade margins, some idea can be obtained of the percentage of time in a year during which the bit-error rate over a typical link rises above 1 in 10^5. Table 1b gives values for these percentage times which were calculated using rainfall data for the south-east of England. However, only scant rainfall data was available and the percentage times given can only be considered as approximate. For reference, Appendix C gives the graph of the estimated percentage times that a given atmospheric attenuation between the earth and the satellite is

TABLE 1a

System margins for digital television transmission (via 'Eurobeam' satellite antenna)

System	E/N_o margin	Estimate of down-link fade margin	Estimate of up-link fade margin
Nominal OTS (Channel 2)	13 dB	10 dB	more than 15 dB
Typical ECS (60 Mbit/s)	4.5 dB	3.5 dB	12 dB
(120 Mbit/s)	1.5 dB	1.0 dB	8 dB
Worst case ECS (60 Mbit/s)	3.5 dB	2.5 dB	11 dB

TABLE 1b

Percentage of time during a year that down-link and up-link fade margins of Table 1a are exceeded

System	% of time down-link fade margin exceeded	% of time up-link fade margin exceeded
Nominal OTS (Channel 2)	negligible	negligible
Typical ECS (60 Mbit/s)	.01	.002
(120 Mbit/s)	.1	.007
Worst case ECS (60 Mbit/s)	.02	.003

exceeded in the south-east of England for both the up-link at around 14 GHz and the down-link at around 11 GHz.

It can be seen that the quality of a single-channel link is more likely to suffer from fading on the down-link rather than the up-link, although in all the cases described it is estimated that the link would be acceptable for at least 99.9% of each year.

6.2 Co-channel interference experiments

6.2.1. General description

In the OTS or ECS systems there will be a degree of co-channel interference caused by imperfect isolation between the orthogonal carrier polarisations of separate channels occupying the same frequency band. Co-channel interference occurs on both the up-link and down-link transmission paths and, in particular, the level of interference between channels is a function of the rate of rainfall (which causes depolarisation of the 14 GHz and 11 GHz carriers) and of the accuracy of the polarisation alignment at the ground stations.

The minimum specified cross-polar discrimination ratio within the 'elliptical' Eurobeam coverage area is 32 dB (for ECS) under clear weather conditions, and it is predicted that under poor weather conditions, atmospheric depolarisation could produce wanted carrier-to-interference ratios of around 24 dB.[9]

Most of the co-channel interference tests were carried out using Channels 2 and $\overline{2}$. In view of the failure of the satellite travelling-wave tube in Channel $\overline{2}$ these tests could only measure the effects of interference over the up-link transmission path.

6.2.2. Test procedures

A digital television test signal was transmitted and received via Channel 2 and a second interfering signal was transmitted over the up-link path on Channel $\overline{2}$. The interference normally comprised a second 60 Mbit/s digital television signal in which 6-bit p.c.m. differences were transmitted to simulate a d.p.c.m. signal. An analogue f.m. television signal was also used as interference in some tests. During the tests the weather conditions were generally good and the presence of an interfering signal produced a negligible change in the wanted channel bit-error rate. Therefore, the effects of co-channel interference produced by more severe weather conditions were simulated in two ways. These were:

(i) The up-link power was faded on the wanted channel while a full-strength modulated carrier was radiated on the interfering channel.

(ii) A fixed ratio of wanted signal and interfering signal were mixed into Channel 2 using a variable power combiner at the input to the ground station aerial.

Both sets of tests were performed for a range of non-linearity in the link high-power amplifiers and for a range of E/N_0 values.

6.2.3. Preliminary co-channel interference measurements

Some preliminary tests were performed to see whether or not co-channel interference effects were dependent on the interfering signal source. 60 Mbit/s video signals were passed through both wanted and interfering channels and arrangements of the same or different video sources with locked or unlocked clocks were tested but none gave significantly different link performance. The only important parameter was whether the 60 MHz multiplex clocks were locked or not, and then the performance was dependent on the relative timing of the phase transitions in the 4-phase p.s.k. modulated carrier. Generally, the 60 MHz multiplexer clocks were left unlocked which gave performance close to that of the worst-case phase shift for the locked condition.

6.2.4. Co-channel interference results

(a) with up-link wanted channel fading.

With no reduction in up-link power, the co-channel interference level that existed on the days when these tests were performed produced no noticeable change in the wanted channel bit-error rate. The wanted channel up-link power was then reduced until the presence of signal on the interfering channel produced a 'significant' change in wanted channel performance. It was found that when the up-link power was dropped by 10 to 12 dB (from that level which just saturated the satellite), co-channel interference caused a doubling

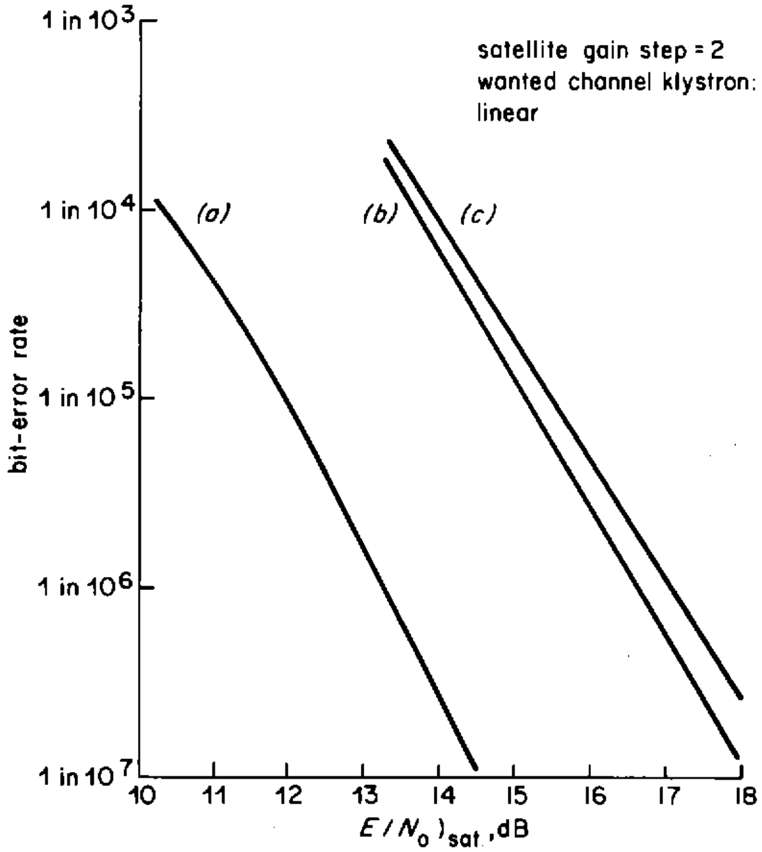

Fig. 9 - Satellite receiver performance in presence of co-channel interference

(a) wanted channel input back-off = 0 dB, with or without interference
(b) wanted channel input back-off = 12 dB, without interference
(c) wanted channel input back-off = 12 dB, with interference

of the bit-error rate at an error rate of around 1 in 10^6.

For example, Fig. 9 shows how the bit-error rate changed in the presence of a signal on the interfering channel and a 12 dB up-link power fade for a range of $E/N_0)_{sat.}$ values. $E/N_0)_{sat.}$ refers to the initial receiver E/N_0 value with the satellite output at saturation.

The change in bit-error rate introduced by co-channel interference appeared to be independent (within the accuracy of our measurements) of the level of non-linearity in either the wanted or interfering channels and also independent of whether the interfering channel carried analogue or digital television signals.

(b) with the addition of an interfering signal to the wanted channel

A low level of the output of the interfering channel was added into the wanted channel and Fig. 10 gives an example of how the bit-error rate varied as a function of carrier-to-interference ratio and link E/N_0 value.

Again, the effect of interference, for a given up-link carrier-to-interference ratio, was not dependent on whether the interfering channel carried digital or analogue video signals nor was the effect obviously dependent on the level of non-linearity of the high-power amplifier of the interfering channel.

From the simulated co-channel interference measurements, system margins were obtained in terms of the E/N_0 margins that existed in the present of interference before the bit-error rate reached 1 in 10^5. Table 2 gives the measurements of E/N_0 margins for a 'typical' ECS receiving terminal (with a clear weather E/N_0 value of 16.8 dB) for different carrier-to-interference ratios and for typical and worst-case levels of linearity of the transmitting station high-power klystron. The transmitted bit rate is taken to be 60 Mbit/s. For 120 Mbit/s transmission each margin is reduced by 3 dB. A graph, also derived from the test results, is given in Appendix D showing the link E/N_0 value required in the presence of co-channel interference to keep the measured bit-error rate below 1 in 10^5.

Note that these results refer to co-channel interference on the up-link path only. The effects of interference on the down-link path have been shown in preliminary tests performed by the Post Office to be approximately equal to the effects of interference on the up-link path for carrier-to-interference ratios above 20 dB. If the same

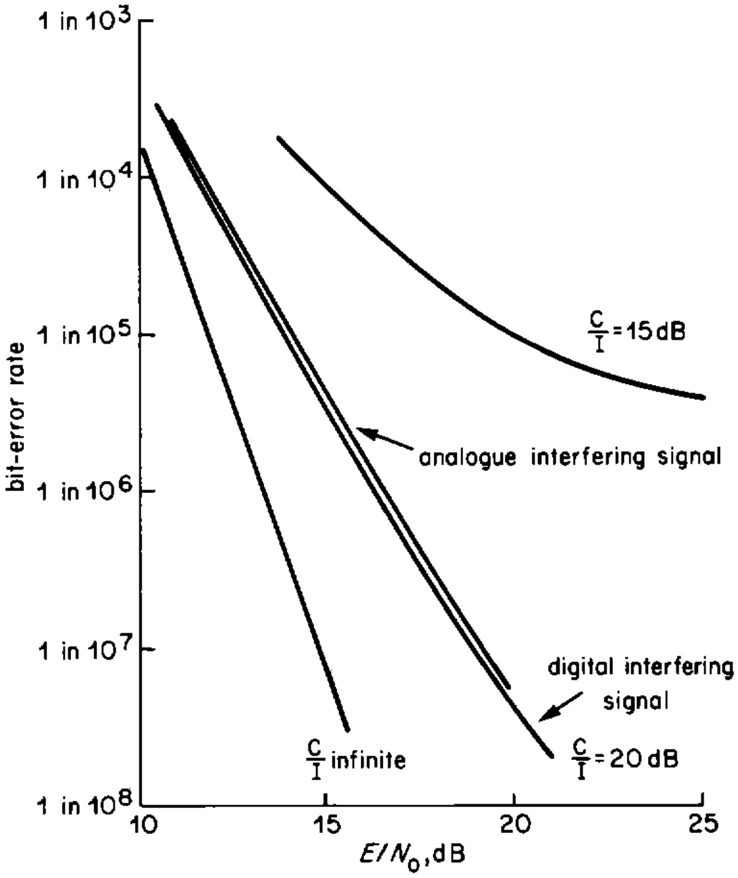

Fig. 10 - Channel 2 performance in presence of simulated co-channel interference. (Wanted channel: satellite input back-off = 2 dB, ground-station klystron operating point-linear)

TABLE 2

Typical ECS receiver E/N_0 margins in the presence of co-channel interference (error-rate limit : 1 in 10^5)

Operating point of ground station klystron	Carrier-to-interference ratio		
	∞ dB	25 dB	20 dB
linear	5 dB	4 dB	3 dB
3 dB output back-off*	4.5 dB	3.5 dB	2.5 dB
At saturation	3.5 dB	3 dB	1 dB

* estimated values

interfering signal is present on both up- and down-links, there exists the possibility of coherent combination of the up-link and down-link interference. This could produce interference levels as much as 3 dB worse than that indicated by a simple power addition of two incoherent interfering signal levels. However, it is thought that the previously-stated figure of 24 dB represents the carrier-to-interference ratio under worst-case conditions of coherence and depolarisation.[9]

6.2.5. Performance estimates in the presence of co-channel cross-polar signals

On the down-link path from the satellite, rainfall which gives rise to depolarisation (resulting in co-channel interference) is also likely to produce attenuation of the wanted channel signal. Therefore, the single channel, down-link fade margins given in Table 1 are reduced by the presence of a co-channel, cross-polar signal. Over the up-link, however, provided that co-channel signals are not radiated from the same ground station, depolarisation of the interfering channel signal and fading of the wanted channel signal will be independent, since it is unlikely that poor weather conditions will exist simultaneously at separated transmitting sites. Therefore, it is most likely that conditions on the down-link path will be the cause of excessive error rates in the 'typical' ECS system.

Making the pessimistic assumption that worst-case carrier-to-interference conditions (~ 25 dB) exist, Table 2 shows that the single channel E/N_0 margins are reduced by 1 dB. Then, from the rainfall attenuation statistics at 11 GHz given in Appendix C, it is estimated that for 60 Mbit/s signals in the presence of a co-channel, cross-polar signal the error rate would rise above 1 in 10^5 for approximately 0.02% of the time (or roughly 2 hours/year) in a 'typical' ECS system. For 120 Mbit/s transmission this figure rises to approximately 0.3% (or roughly 30 hours/year). These percentage figures are close to the equivalent single channel percentages (Table 1b) confirming the success of the so-called 'frequency re-use' technique adopted for OTS and ECS.

6.3. Adjacent-channel interference experiments

6.3.1. General

In the ECS system the basic channel spacing will be 83.33 MHz. Separation between channels is controlled by filters at the transmitting and receiving sites and by filters at the input and output of the satellite repeater. At the transmitter the filtering is performed prior to high-power amplification. If, then, the amplifier is near saturation, the non-linear response gives rise to high-frequency components outside the specified channel bandwidth. This spectrum spreading gives rise to interference on the up-link path in adjacent channels with the same polarisation. The interference increases in level as the ground station amplifier is taken further into saturation. At worst, at an ECS system station, an amplifier might be run at saturation.

Non-linearity in the satellite travelling-wave tube gives rise to further spectrum spreading. However, adjacent-channel interference on the down-link is limited to a low level by filters at each repeater channel output.

For 60 Mbit/s digital television transmission via the ECS, if the signal spectrum occupies the central region of the 80 MHz channel bandwidth then interference from adjacent channels will be at a very low level within the wanted signal bandwidth. However, for 120 Mbit/s television transmission, the interference spectrum may overlap

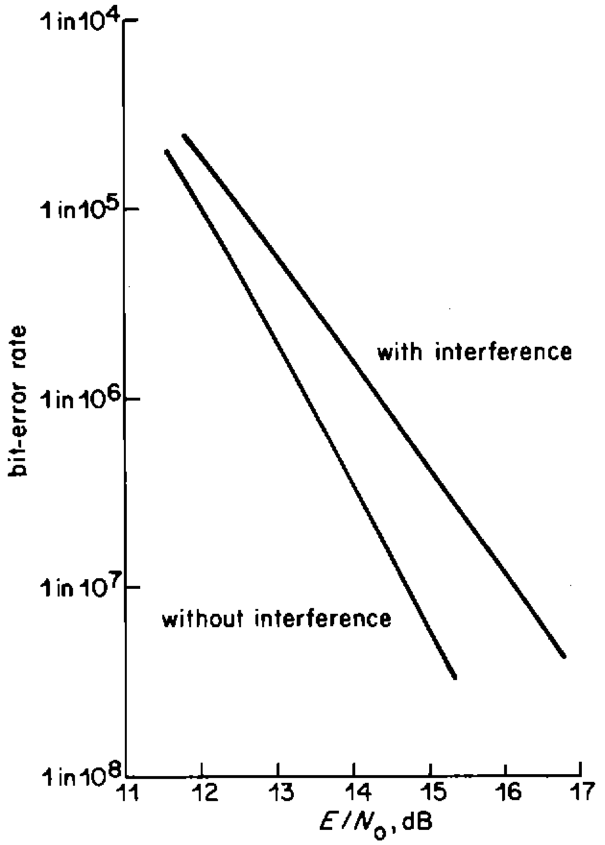

Fig. 11 - Channel 2 performance showing effect of simulated adjacent-channel interference

Link operating conditions:
satellite; input back-off = 0 dB, gain step = 4
ground-station klystrons; wanted channel — linear, interfering channel — 0 dB output back-off

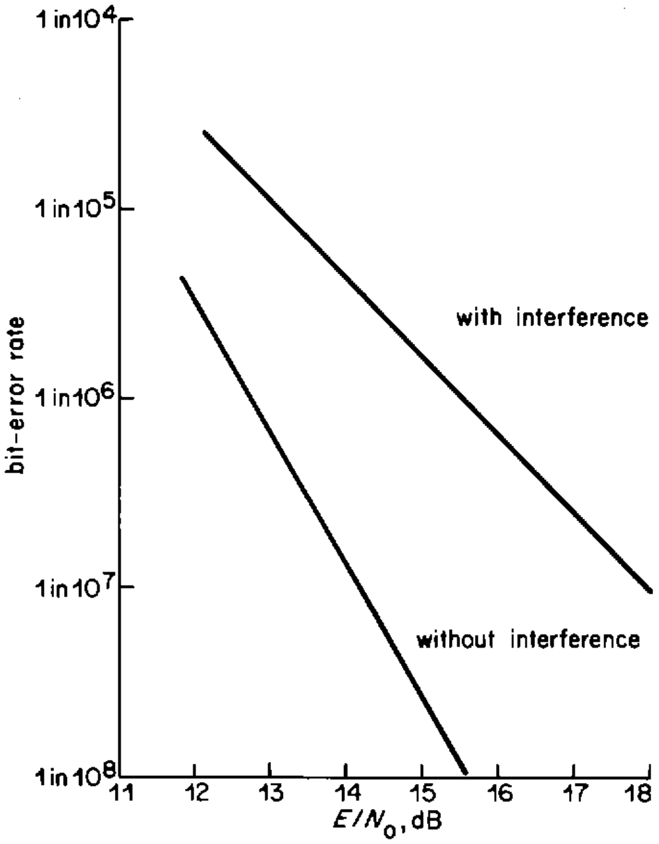

Fig. 12 - Channel 2 performance showing effect of adjacent-channel interference and wanted channel fading

Link operating conditions:
satellite; input back-off = 5 dB, gain step = 4
ground-station klystrons; wanted channel — linear, interfering channel — 0 dB output back-off

the signal spectrum giving rise to degradation in the wanted channel performance.

6.3.2. Adjacent-channel interference measurements using the OTS

Adjacent-channel interference was examined using the OTS by transmitting a 60 Mbit/s digital video signal on Channel 2 and an interfering 60 Mbit/s digital video signal on an adjacent channel with the same polarisation. The carrier frequency for the second transmission channel was set, for these measurements, at a spacing of 42.67 MHz from the Channel 2 carrier frequency. With this spacing, the Channel 2 performance corresponded to that of an ECS channel carrying 120 Mbit/s data for a given level of non-linearity in an adjacent channel also carrying 120 Mbit/s data. The OTS figure of 42.67 MHz takes into account a slight difference in channel filter characteristics between the OTS and the ECS systems.

The interfering channel carrier was radiated at full strength (at a level which would saturate a satellite channel) and the klystron in this channel was run at saturation. This represents worst-case conditions and Fig. 11 shows the effect of interference from this adjacent channel on the Channel 2 performance.

A wanted channel up-link fade increases the performance degradation produced by adjacent-channel interference. Fig. 12 demonstrates the change in link performance when the wanted channel power was reduced by 5 dB.

The level of adjacent-channel interference was reduced to a more typical level by changing the output back-off of the interfering channel klystron to 3 dB, while maintaining the same radiated power. The presence of interference did not then produce any significant change in the bit-error rate until the wanted channel up-link power had been faded by more than 10 dB.

TABLE 3

ECS system margins in the presence of adjacent-channel interference for 120 Mbit/s digital television transmission

Interfering channel klystron output back-off	E/N_0 margin	Up-link fade margin	Down-link fade margin
0 dB	0.8 dB	3 dB	0.5 dB
3 dB	1.5 dB	8 dB	1 dB

6.3.3. System margins

From the results, some estimates of E/N_0, down-link and up-link fade margins for the ECS system were obtained for 120 Mbit/s digital television transmission in the presence of adjacent-channel interference. These are given in Table 3, for an upper bit-error-rate limit of 1 in 10^5.

For 60 Mbit/s digital television transmission via the ECS the single channel system margins will be unaffected by adjacent-channel interference.

7. Other tests

For the majority of tests the received picture quality, with the error corrector in operation, was indistinguishable from that transmitted. At a bit-error-rate of 1 in 10^5 the presence of errors was just perceptible in the received pictures. The Post Office error pattern measuring equipment confirmed that the occurrence of errors was essentially random.

Owing to a small motion in the exact satellite position relative to the Goonhilly station, the received carrier was slightly Doppler-shifted in frequency from the transmitted carrier. This resulted in a difference in the colour-subcarrier frequencies between the transmitted and received signals of typically .03 Hz.

In order to demonstrate re-transmission of a digital television signal by a second earth station, 60 Mbit/s signals were sent via Channel 4 of the OTS to Bercenay where they were looped around at i.f. without digital demodulation and then sent back to Goonhilly via Channel 4. Despite non-optimised channel-shaping filters at Bercenay resulting in a rather high bit-error rate of 5 in 10^6, excellent reception of television pictures was obtained.

Using the time delay in this circuit (approximately ½ second), a small clip of picture was locked into the system by again looping the signal at Goonhilly by using the decoded television picture signal (decoded from 6-bit d.p.c.m. to 8-bit p.c.m. only) as the source for transmission. This demonstrated that even after more than 70 times* around the satellite loop (more than 140 hops) the picture quality was identical to that of the input except for the addition of one or two small error streaks that had resulted from overloading of the error correction system. Although the satellite loop did not contain an exact number of pictures, it was just possible to make a video recording of this test.

8. Conclusions

60 Mbit/s digital signals consisting of multiplexed digital video and sound data were sent via the OTS from Goonhilly Downs Earth Station during a series of transmission tests conducted by the Post Office in conjunction with the BBC during February 1979. The majority of the tests were carried out using the 40 MHz bandwidth OTS channel and the 'Eurobeam A' satellite antenna.

Preliminary tests showed that six-stage scrambling of the video data was required before the channel bit-error rate was independent of the picture source and independent of whether the data was coded as p.c.m. or d.p.c.m.

The bit-error rate over the satellite channel was monitored for a range of simulated transmission and reception conditions, in particular those conditions which are specified for television transmission via large earth stations in the future ECS network. Table 4 summarises the measured bit-error rates for the nominal OTS system at Goonhilly and for the simulation of a 'typical' ECS system for both 60 Mbit/s and 120 Mbit/s data rates.

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* The number of times round the satellite loop was limited by the eventual mis-clocking of the received data. This was caused by an accumulating phase difference between the ground-station data clock and the received data as a result of the Doppler shift produced by the satellite movement.

TABLE 4

Single channel performance

System	E/N_0	Bit-error rate
Nominal OTS (60 Mbit/s)	25 dB	negligible
Typical ECS (60 Mbit/s)	16.8 dB	less than 1 in 10^8
Typical ECS (120 Mbit/s)	13.8 dB	1 in 10^6

TABLE 5

E/N_0 margins from typical system operating conditions

System	No interference	C.C.I. C/I ≏ 25 dB	A.C.I. (worst case)
Nominal OTS (60 Mbit/s)	13 dB	12.5 dB	not applicable
Typical ECS (60 Mbit/s)	4.5 dB	3.5 dB	4.5 dB
Typical ECS (120 Mbit/s)	1.5 dB	0.5 dB	0.8 dB

TABLE 6

Estimates of the time during a year that the error rate exceeds 1 in 10^5

System	with no interference	with a co-channel signal	with A.C.I. (worst case)
Typical ECS (60 Mbit/s)	0.01% (≃ 1 hr.)	0.02% (≃ 2 hrs.)	0.01% (≃ 1 hr.)
Typical ECS (120 Mbit/s)	0.1% (≃ 9 hrs.)	0.3% (≃ 26 hrs.)	0.2% (≃ 18 hrs.)

Bit-error rates were also measured under simulated conditions of co-channel and adjacent-channel interference. System margins were obtained in terms of the degradations in link E/N_0 value and corresponding down-link and up-link power fade values that could be tolerated before the bit-error rate reached an upper limit (1 in 10^5) chosen as acceptable for digital television transmission. Table 5 summarises the E/N_0 margins for the OTS system and for a 'typical' ECS system with no interference and with predicted worst-case interference conditions.

Some estimates were also made of the length of time for which the error rate would rise above 1 in 10^5 because of poor weather conditions. These estimates are summarised in Table 6 for a typical ECS channel in the presence of either a co-channel, cross-polar signal or an adjacent-channel, co-polar interfering signal.

It was shown that in all cases the bit errors occurred essentially at random and for typical operating conditions of both the OTS and ECS systems the received picture was indistinguishable from the transmitted picture. In particular, the so-called 'frequency re-use' aspects of the OTS and ECS systems did not appear to cause large changes in the performance margins. A single ECS channel could, therefore, be used to carry high-quality television signals in the form of one 60 Mbit/s signal or two such signals interleaved to give a 120 Mbit/s data stream. The system margins are greater, however, for the 60 Mbit/s signal.

9. Acknowledgements

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appreciated, and Ampex of Great Britain Ltd. kindly loaned portable television recording equipment for the duration of these trials.

10. References

1. OSBORNE, D.W. 1976. Experimental digital transmission of multiplexed video and audio signals at 120 Mbit/s. BBC Research Department Report No. 1976/16.
2. REID, D.F., STOTT, J.H. *and* OSBORNE, D.W. 1977. Experimental digital transmission of multiplexed video and audio signals at 60 Mbit/s through a satellite. BBC Research Department Report No. 1977/32.
3. GILCHRIST, N.H.C. 1978. Digital transmission of multiplexed video and audio signals at 140 Mbit/s over an experimental optical-fibre transmission system. BBC Research Department Report No. 1978/32.
4. Analogue television tests with OTS. To be published jointly by the EBU and Interim Eutelsat.
5. DEVEREUX, V.G. *and* PHILLIPS, G.J. 1974. Bit-rate reduction of video signals using differential p.c.m. techniques. International Broadcasting Convention 1974. IEE Conference Publication No. 119, pp. 83 – 89.
6. STOTT, J.H., OLIPHANT, A. *and* OSBORNE, D.W. 1974. Digital video: error correcting codes and a practical study of a Wyner-Ash error corrector. BBC Research Department Report No. 1974/40.
7. CROLL, M.G., OSBORNE, D.W. *and* SPICER, C.R. 1974. Digital sound signals: the present BBC distribution system and a proposal for bit-rate reduction by digital companding. International Broadcasting Convention 1974. IEE Conference Publication No. 119, pp. 90 – 95.
8. STOTT, J.H. 1976. 60/120 Mbit/s multiplexing equipment for high-quality video and audio signals. BBC Research Department Report No. 1976/31.
9. HARRIS, R.A. 1978. Transmission aspects of the European Communications Satellite (ECS) System. ESA Journal 1978, Vol. 2, pp. 259 – 277.
10. PANTER, P.F. 1972. Communication systems design: line of sight and troposcatter systems. McGraw-Hill.

Appendix A

11. OTS transponder gain relative to nominal gain-step setting (7) for Channel 2

Gain step	Channel 2 transponder gain (dB relative to gain step = 7)
0	−9.77
2	−6.41
4	−3.30
6	−1.15
7	0
8	+1.00
10	+2.70
15	+5.20

(The overall gain at saturation at gain step 7 is nominally 108.3 dB.)

Appendix B

12. Energy contrast ratio E/N_0

The E/N_0 value for a digital link is defined as the received energy-per-bit divided by the noise-power-per-unit-bandwidth. The relationship between E/N_0 values and carrier-to-noise ratios for a transmission link is given by:

$$\begin{aligned} E/N_0 &= C/R.\ B/N \\ &= C/N.\ B/R \end{aligned}$$

where
E = received energy per bit (Joule/bit)
N_0 = noise power per unit bandwidth (Watt/Hz)
C = received carrier power (Watt)
R = bit rate (Sec^{-1})
B = bandwidth of noise-measuring filter (Hz)
N = noise power in bandwidth B (Watt)

For example, carrier-to-noise figures for analogue television transmission via the ECS are quoted for a bandwidth of 36 MHz. Then for 60 Mbit/s digital transmissions over a link with the same noise-power-per-unit-bandwidth

$$E/N_0(\text{dB}) = C/N(\text{dB}) - 2.2$$

This E/N_0 value is 3 dB less than the 'normalised' carrier-to-noise power ratio in which the noise power is quoted for a bandwidth equal to the symbol rate (which equals half the bit rate for 4-phase p.s.k.).

Appendix C

13. Rainfall attenuation

13.1. Attenuation statistics

Fig. 13 shows estimates* of the percentage time in a year that a given atmospheric (rainfall) attenuation between an earth station and a satellite at 10° E is exceeded for both the up-link at 14 GHz and the down-link at 11 GHz. The time estimates were extrapolations of data (taken from the CCIR Report 563-1) for Climatic Zone 4 but assuming a slightly drier micro climate for the south-east of England. However, these curves are based on relatively scant data and should only be considered as approximate.

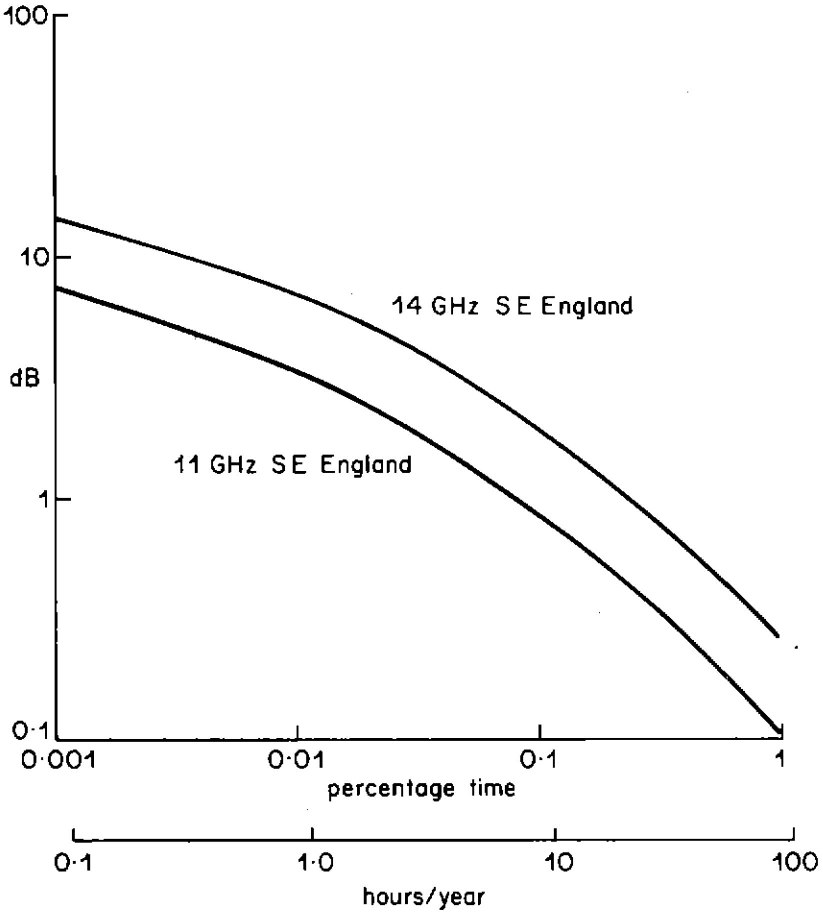

Fig. 13 - Atmospheric (rainfall) attenuation between S.E. England and satellite at 10°E (e.g. OTS, ECS)

13.2 Atmospheric noise contributions

Rainfall attenuation over the down-link path not only reduces the received signal power but also causes an increase in the atmospheric noise level. Fig. 14 gives an estimate of the resulting change in E/N_0 value for a given down-link attenuation, A.

In calculating the change in noise level, the noise power received by the antenna (described in terms of an 'antenna temperature' T_A)^{10} was taken as

$$T_A = 275(1 - 10^{-A/10}) + (T_B + T_S) \,.\, 10^{-A/10}$$

where T_B is the background sky noise in absence of attenuation and T_S is the apparent noise temperature of the satellite signal source resulting from up-link noise contributions. The first term in this expression

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* produced by R.V. Harvey.

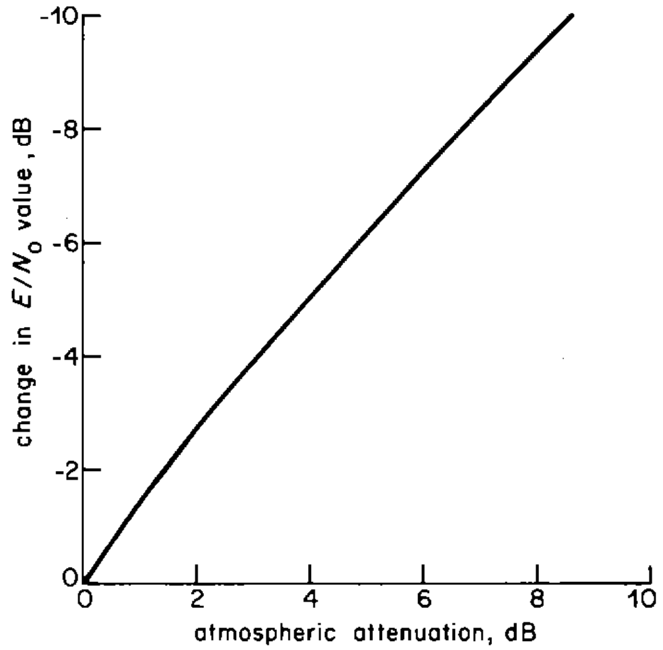

Fig. 14 - Estimate of the change in E/N_0 value with atmospheric attenuation over the down-link path

for T_A is the noise temperature of the noise generated by down-link atmospheric attenuation. Also, in deriving Fig. 14, a receiver noise temperature of 200°K and a feeder loss of 1 dB between antenna and receiver were assumed. In addition, the factor $T_B + T_S$ was taken as 100°K approximating to ECS conditions.

The noise power received by the satellite is not a function of up-link attenuation since the background noise source temperature and the temperature of the attenuation medium are approximately equal.

Appendix D

14. Co-channel interference in measurements

Fig. 15 shows the minimum value of E/N_0 required to keep the error rate below 1 in 10^5 in the presence of co-channel interference. The three curves refer to different operating conditions of the transmitting-station high-power klystron.

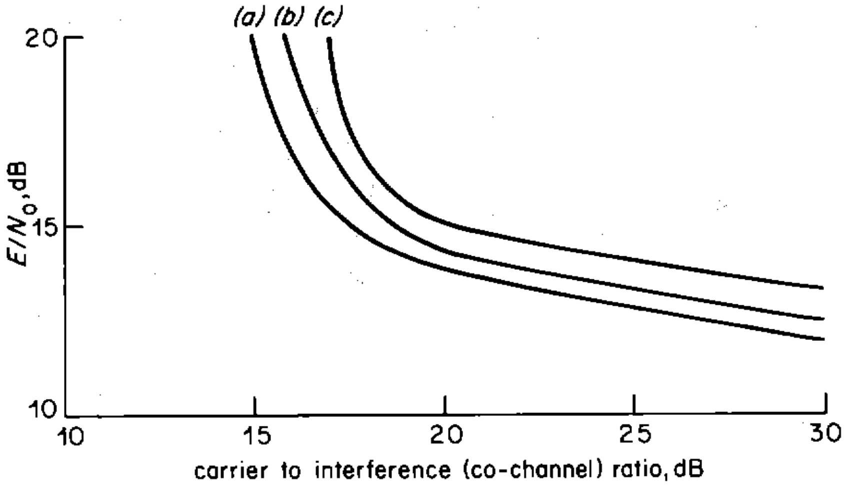

Fig. 15 - Minimum E/N_0 value required for a bit-error rate of 1 in 10^5

Ground-station klystron operating conditions

(a) linear (b) 3 dB output back-off

(c) at saturation

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